ORBIT SIMULATIONS AND RESULTS

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ORBIT: Application to SNS

- ORBIT incorporates realistic physics and engineering assumptions to allow the investigation of detailed physics and design issues in high intensity rings.

- In this presentation I will summarize a number of ongoing SNS ring studies using ORBIT:
  - Postponement of HEBT RF cavities until after CD-4 (Holmes, Henderson)
  - Effect and correction of ring magnet errors (Bunch, Holmes, Cousineau).
  - Providing insight for ring applications (Bunch, Holmes, Plum)
  - Inclusion of injection chicane lattice (Holmes, Henderson, Wang).
  - Painting self consistent uniform elliptical beams (Danilov, Cousineau, Henderson, Holmes).
  - Initial electron cloud studies (Sato, Shishlo, Holmes).

ORBIT : Assumptions for Studies

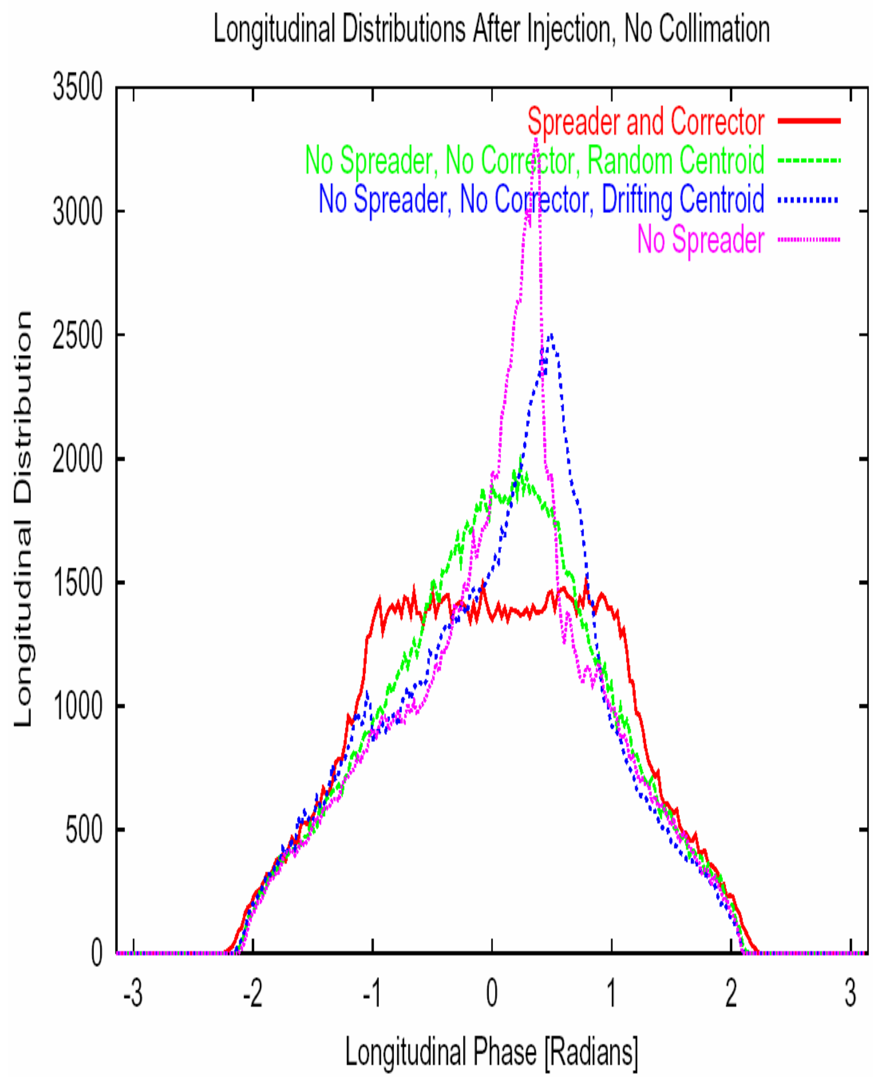
- Dynamics
  - Symplectic single particle tracking, including hard edge fringe fields.
  - Collective effects including space charge and dominant ring impedances.
  - Use 1 GeV proton beam unless specified.
- SNS Ring Lattice
  - Reference tunes $Q_x = 6.23$, $Q_y = 6.20$ and natural chromaticity unless stated otherwise.
  - Magnets organized into chosen families, including dipole and quadrupole correctors.
  - Magnet errors and correction as appropriate.
  - 44 horizontal and vertical BPMs at correct locations.
  - Detailed injection chicane when appropriate.
- Lattice and Dynamics
  - Injection painting and foil hits with proton/foil interactions.
  - Dual harmonic longitudinal RF with four cavities at correct locations.
  - Collimators and apertures for proton losses.
- Diagnostics
  - Profiles and moments.
  - Emittances and tunes.
  - Distributions and losses.

CD-4 HEBT RF Cavity Postponement

- As part of endgame plan, delay of the HEBT energy spreader and corrector cavities until after CD-4 is under consideration.
- While this should present no problems for low intensity operation, it is necessary to demonstrate that 1.0 MW operation can be conducted using the CD-4 accelerator configuration.
- ORBIT studies were carried out to investigate 1 MW operation without the HEBT RF cavities.
- The default ORBIT SNS injection routine includes the effects of both the HEBT energy spreader and corrector cavities. We studied the effects during accumulation in the ring of
  - removing the energy spreader cavity only, which gives a perfect linac beam, and
  - removing both the energy spreader and corrector cavities, which leaves linac energy jitter in the beam.

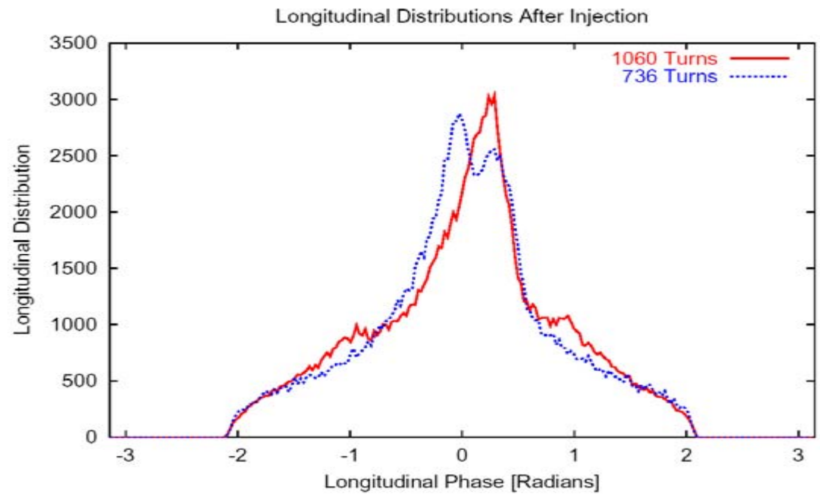
CD-4 HEBT RF Cavity Removal

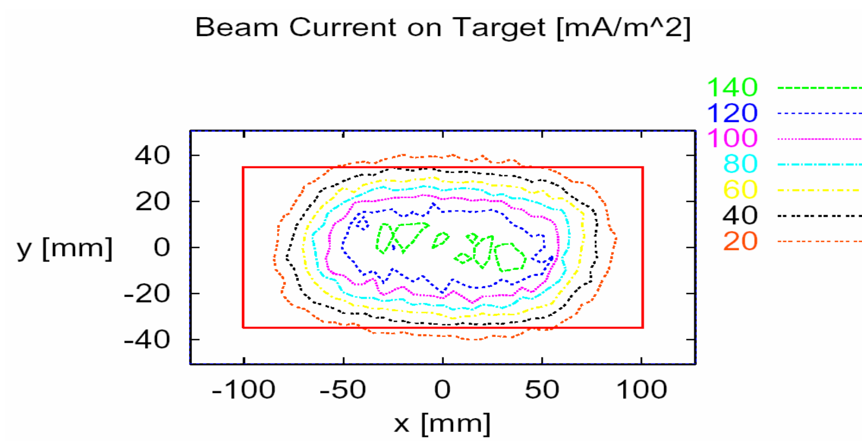
- With 1MW, 1060 turn injection and default painting scheme, removal of HEBT ESC and/or ECC changes injected energy distribution, which leads to peaked longitudinal distributions and increased losses due to bunch factor effects:
- Losses
  - With both cavities: 0.006%
  - Remove spreader only (perfect linac beam): 0.41%
  - Remove spreader and corrector, random centroid jitter: 0.003%
  - Remove spreader and corrector, drifting centroid: 0.22%



CD-4 HEBT RF Cavity Removal

- Concentrate on **worst case** – energy spreader removed, which is equivalent to a **perfect linac with both cavities removed**.
- **Adjust painting**
  - **736 turns** at full linac intensity cures bunch factor effects. The longitudinal distribution still becomes peaked, but there isn't time for significant beam loss. Losses become: 0.014%
  - Paint **broader transverse distribution** to limit maximum current density. Beam on target parameters: 93% reaches target footprint, 155 mA/cm^2 peak current density.
- **Conclusion: We can operate the ring at 1 MW without the ESC and ECC.**





Alignment and Field Errors in the Ring

- Comprehensive studies of ring magnet errors and their correction are underway.
- We present here the results of some initial studies on the effect and correction of dipole and quadrupole displacement, field strength errors, and quadrupole roll errors.
- Displacement errors are horizontal or vertical misplacements of a magnet without pitch, yaw, or roll. ORBIT contains models for these latter effects, and they are now under study.
- Field strength errors are incorrect values of the field strengths. ORBIT also contains models incorporating higher field harmonics, but those are yet to be studied.
- In all studies, we consider both specified individual errors as well as random sets of magnet errors applied throughout the ring.

Errors Perturbing the Closed Orbit

- For errors that perturb the closed orbit, we focus on orbit deflection and losses:
  - Deflection:
    - Closed orbit calculation
    - "Standard pencil beam" with initial coordinates at injection point placed on desired closed orbit
  - Losses are studied for full 1.44 MW injection scenario:
    - $1.5*10^{14}$ protons at 1 GeV
    - Scrapers, collimators, and beam apertures around the ring are included

Correction of Errors Perturbing the Closed Orbit

- Carry out error correction for standard pencil beam by setting dipole corrector strengths to minimize BPM signals:
  - 44 horizontal, 44 vertical BPMs - with or without random BPM uncertainties
    - Truncated gaussian distribution: σ=0.5 mm, Max = 1 mm
  - 24 horizontal, 28 vertical dipole corrector strengths
  - Least squares:
    - Minimize sum of squares of BPM signals (beam dipole moments)
    - Use standard pencil beam
    - Apply scheme to individual as well as to random sets of magnet displacements.
- Calculate losses with full injection simulations for uncorrected and corrected cases, with and without random BPM uncertainties.

Quadrupole Field Strength Errors and Correction

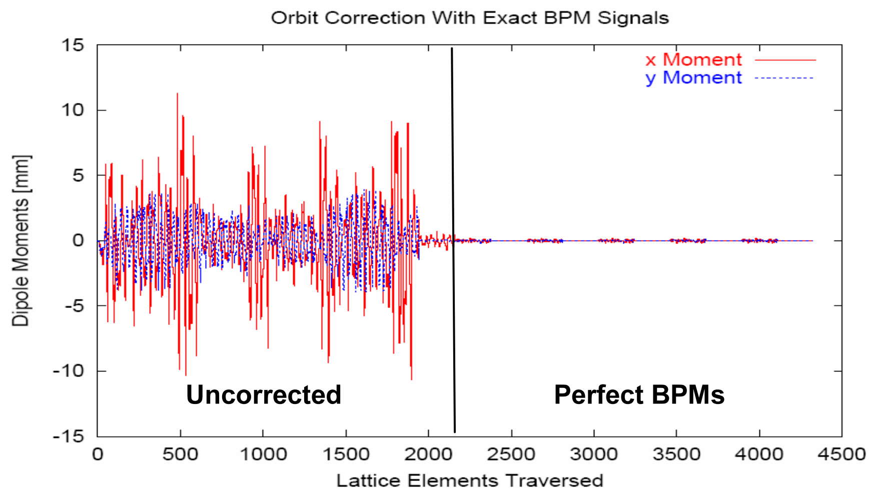
- Quadrupole field strength errors alter the beta functions, dispersion, and tunes.
- For these errors, we focus on betatron phase advances and losses, with the loss calculations as before.
- We now consider family as well as random sets of errors:
  - There are 6 main quadrupole families in the ring, each on its own power supply.
  - Random errors within families are at the 10^{-4} level, which we include, but family errors in the percent range are dominant.
- Carry out error correction by setting quadrupole strengths, obeying family current constraints, to match betatron phase advances calculated from BPM signals:
  - 44 horizontal, 44 vertical BPMs - with or without random BPM signal uncertainties
    - Gaussian distribution: σ=3.6°
  - 6 main families and 16 additional trim quad families. So far, only using 6 main families.
  - Least squares:
    - Match horizontal and vertical betatron phase advances at BPMs.
    - Apply scheme to individual as well as to random sets of magnet field errors.
- Calculate losses with full simulations for uncorrected and corrected cases, with and without random BPM uncertainties, as described above.

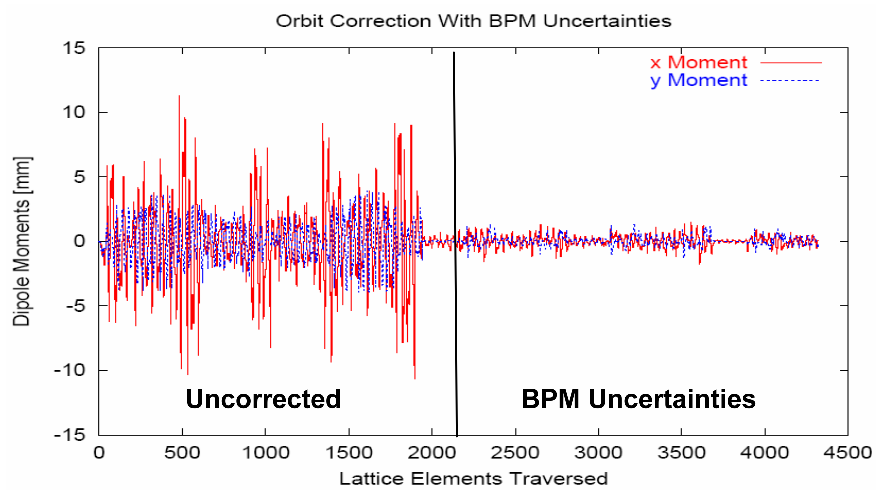
Error Correction Results: Orbit and Phase Correction

- **Errors:**
  - **We typically study errors of larger sizes than are actually anticipated in SNS.**
  - **Studied individual 1 mm displacements, 0.1% dipole field, and 2% quadrupole field (by family) errors.**
  - **Studied random sets of 0.25 mm displacements, 0.1% dipole field, and 1.0% quadrupole field (by family) errors.**
  - **All errors studied assuming perfect BPM signals and alternatively, random BPM signal errors leading to 0.5 mm in dipole moment or 3.6° in phase.**
- **Correction:**
  - **Orbit correction is good to ~ 1 mm assuming BPM uncertainties, better with perfect BPM signals.**
  - **Required dipole kicker strengths are < 0.5 mradians, well within capabilities.**
  - **Phase correction is comparable to the assumed BPM phase uncertainty; for perfect BPM signals, tunes are accurate to within $3*10^{-4}$.**

Random Errors:
Losses With and Without Correction

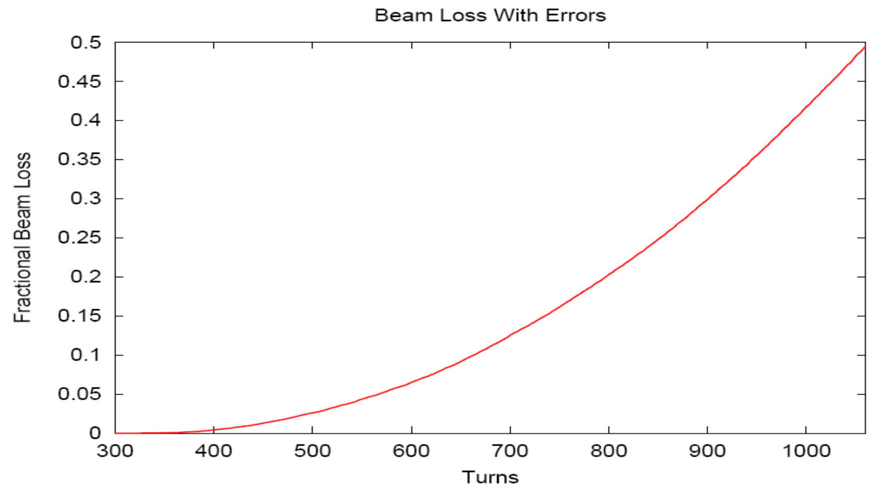
- Calculations were carried out with simultaneous activation of **random sets** of errors:
  - **SNS tolerances, or worse**, were used
    - 0.25 mm for all displacement errors
    - 0.1% for dipole field errors
    - 1.0% for quadrupole field errors (by family)
    - 0.2 mr quadrupole roll errors
  - Random seeds were varied to find some bad loss cases
  - **Losses with errors varied from less than 1% to ~ 50%**
  - **Correction was applied to some cases with significant losses**
    - Both exact BPM signals and BPM signal uncertainties were considered

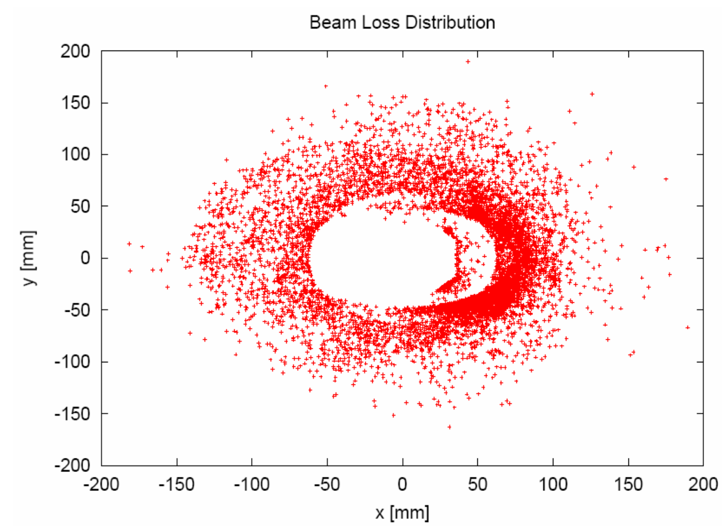




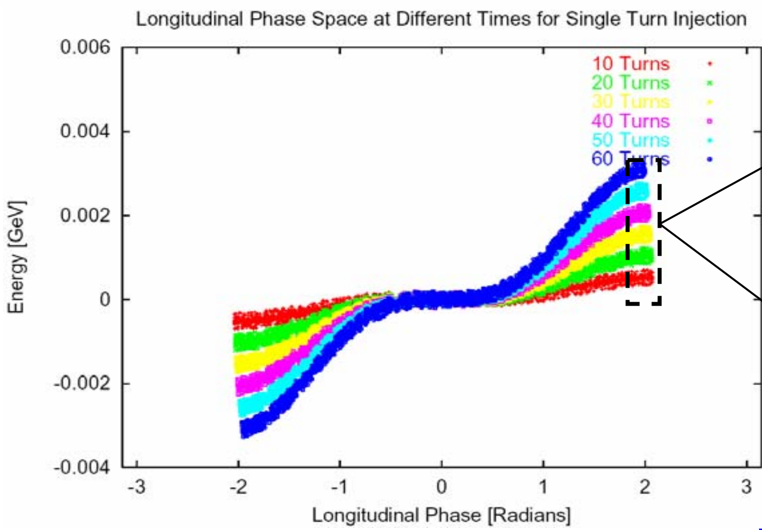
Results: Losses With and Without Orbit and Phase Correction

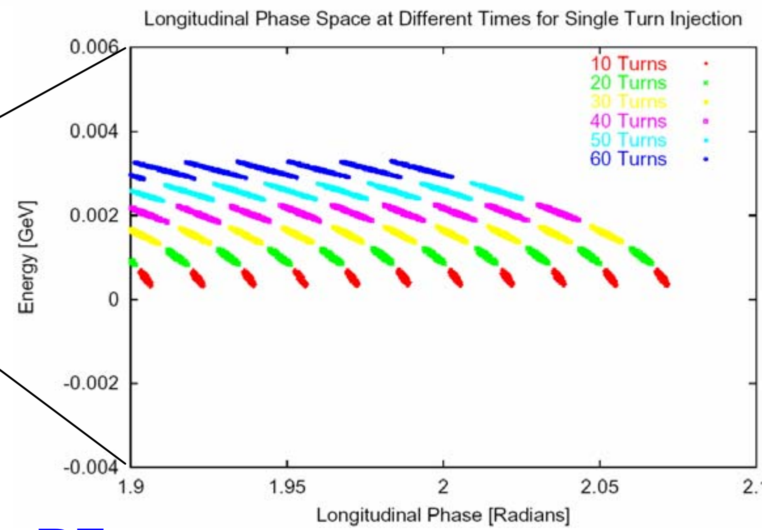
- **Without correction, 49%** **of the beam is lost, starting before 400 turns.**
- **With orbit correction, assuming no BPM errors, losses are $< 10^{-4}$.**
- **With random BPM signal ucertainties, losses are still $1.7*10^{-4}$.**
- **These results have been found to hold in general to cases considered thus far.**



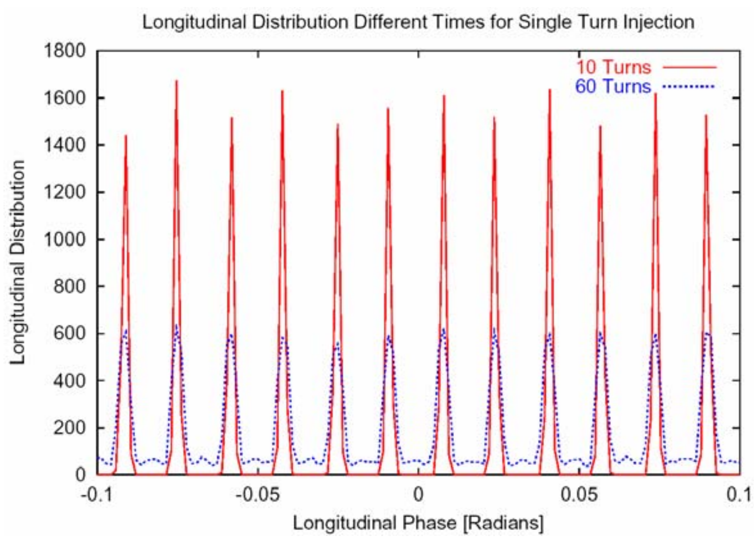


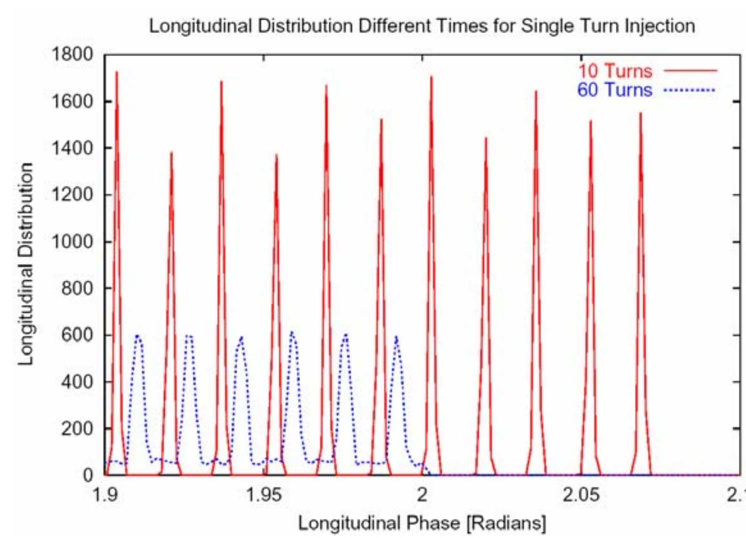
Single Turn Injection: Debunching of Linac Beam in Ring





With RF





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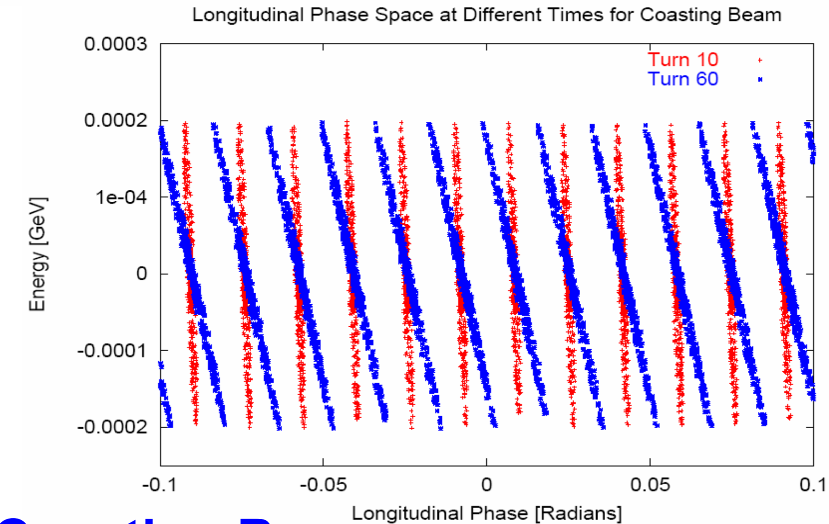
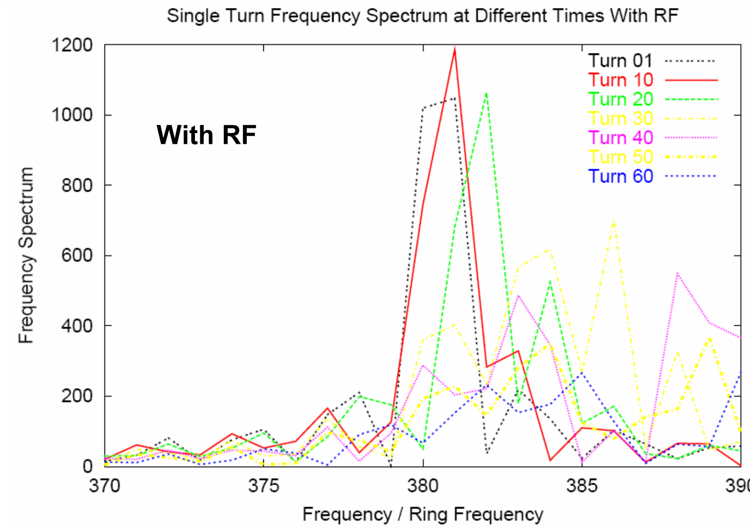
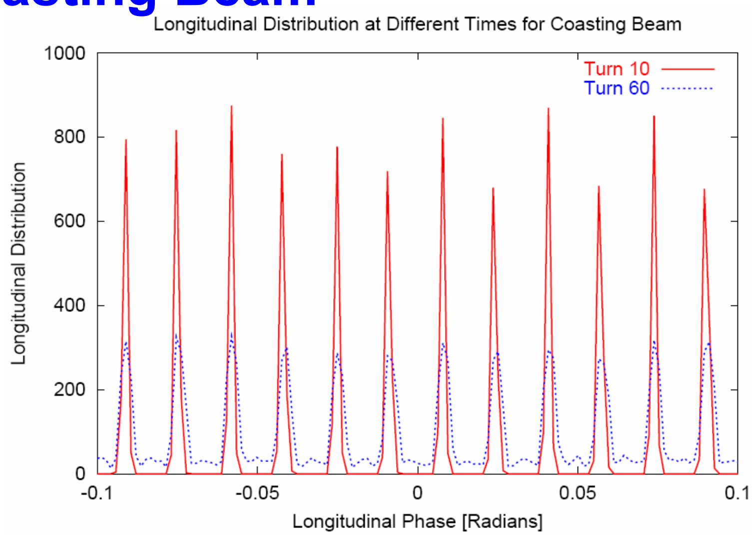
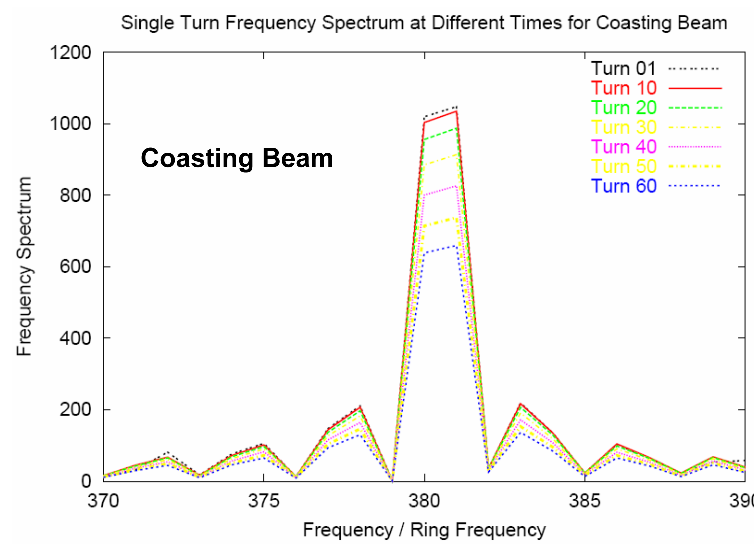




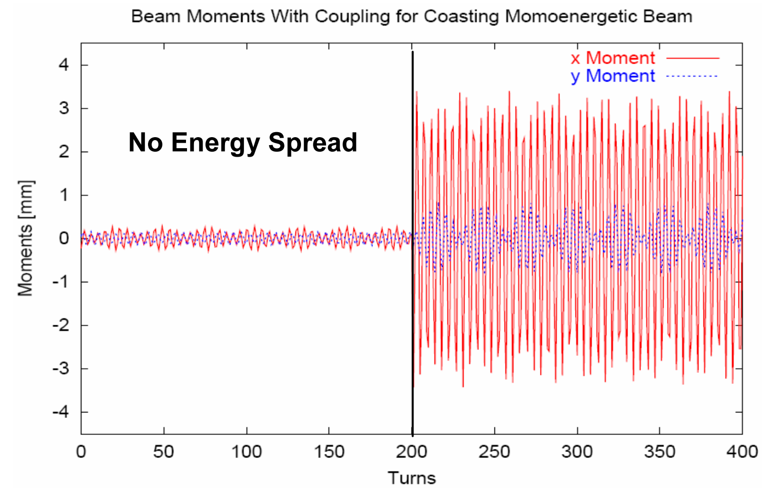
Coasting Beam

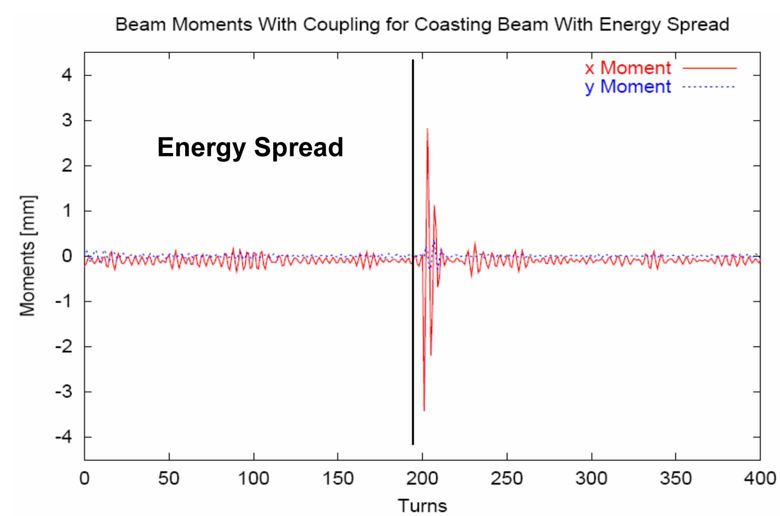




BPM Signals to Determine x-y Coupling: From Dipole Kick of Accumulated Beam

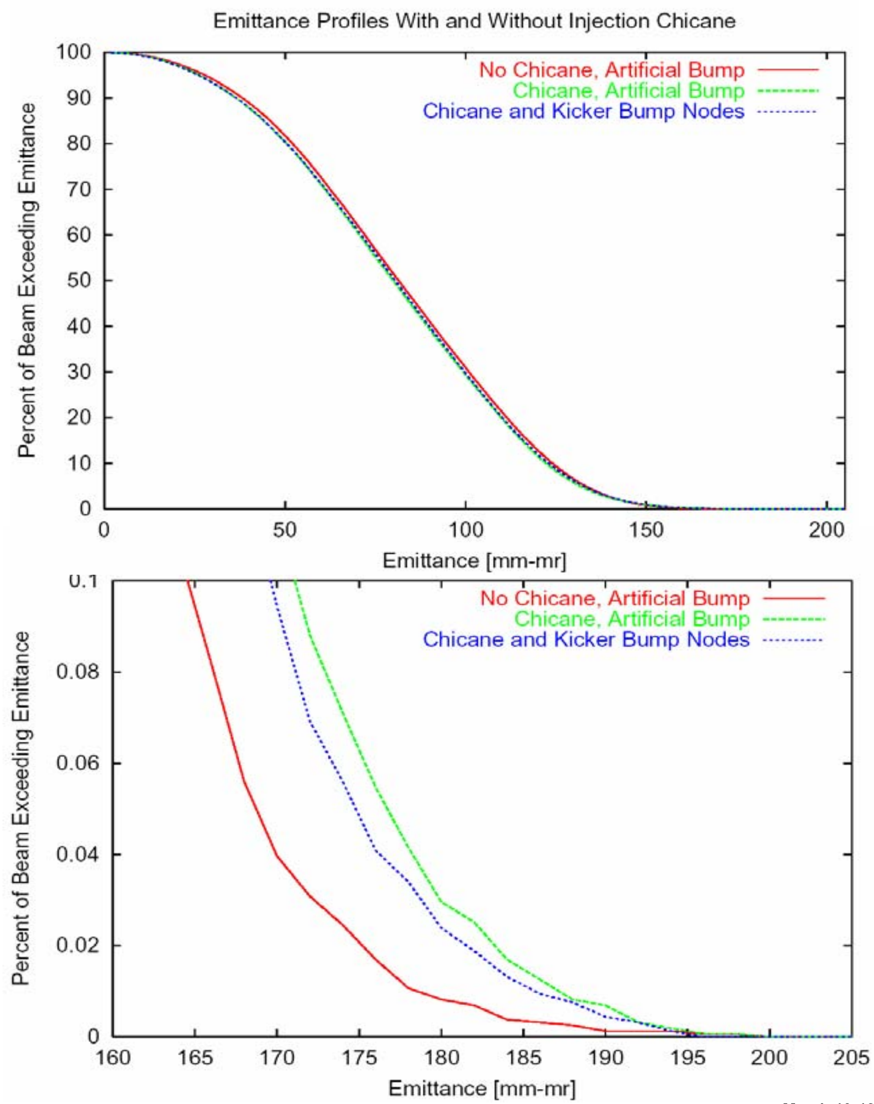
- **Assume x-y coupling:**
- **For a kicked monoenergetic coasting beam, dipole moments oscillate indefinitely with envelope oscillation amplitudes and periods in agreement with analytic model of x-y coupling. This provides:**
  - **Horizontal/vertical tune separation**
  - **Strength of coupling**
- **With energy spread, dipole moments of kicked beam quickly damp.**
- **We are also studying excitation of beam quadrupole moment oscillations with resonant quadrupole kicker.**





Injection Chicane

- We have begun detailed studies of the effect of the injection chicane.
- So far, we have:
  - Incorporated the chicane lattice,
  - Developed time-dependent kicker nodes with programmable kicks, and
  - Tested these capabilities on a standard injection case.
- The next step will be to replace the present simple models for the chicane bends by realistic chicane bend models based on the measured fields. These models are yet to be developed.



March 10-12, 2003

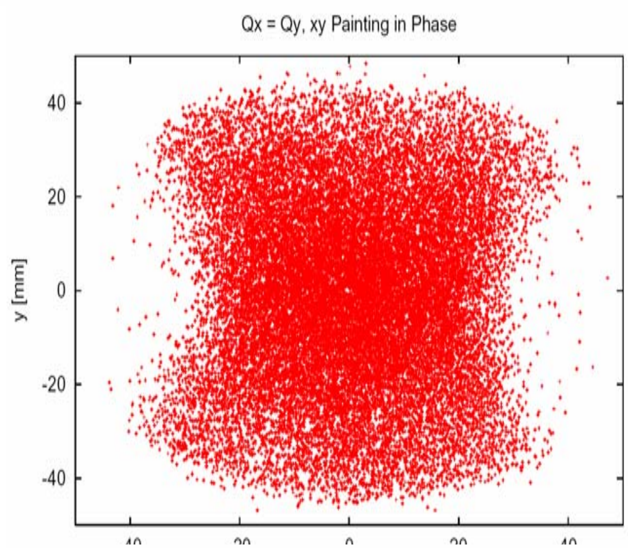
Self Consistent Uniform Elliptical Beams

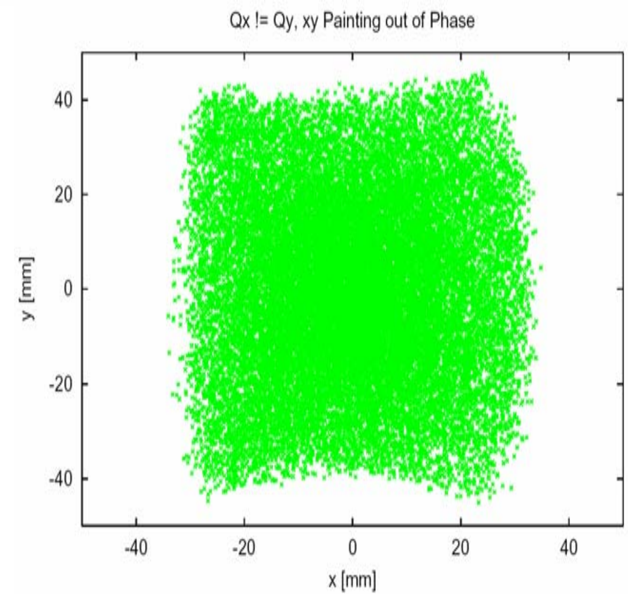
- We have demonstrated (Danilov, et al, accepted by PRST-AB) that
  - there are an infinite number of uniform density elliptical KV-like beams that
  - retain their uniformity and ellipticity under all linear transformations.

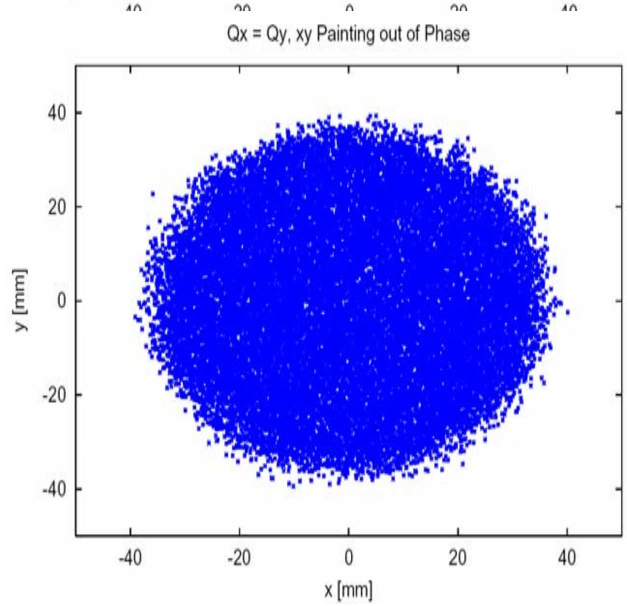
- Such distributions could provide advantages for SNS:
  - Uniform density is desirable from the standpoint of target requirements.
  - Uniform distributions have lower space charge tune shifts.

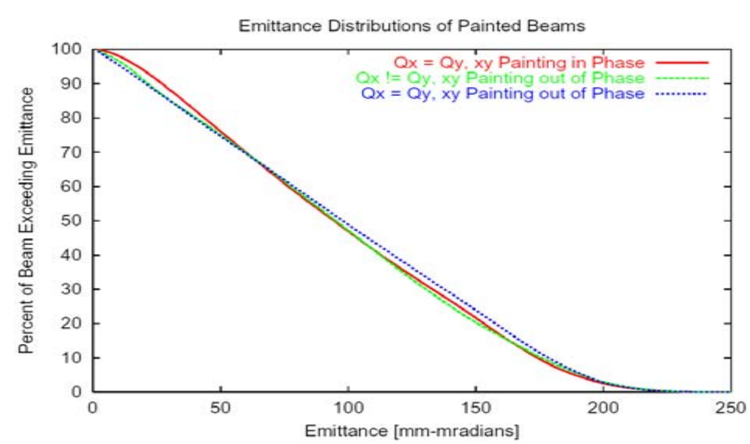
- We have demonstrated a painting scheme to create such a beam in SNS. The scheme requires painting in x´ and y´ as well as in x and y. Specifically, it is required
  - to use nearly equal horizontal and vertical betatron tunes,
  - to paint with linearly increasing (in time) emittances $\varepsilon_x = \varepsilon_y = \varepsilon_f * t / t_f$,
  - to paint with 90° phase difference between the x-x´ and y-y´ planes.

Self Consistent Uniform Round Beams









March 10-12, 2003

ORBIT E-Cloud Model Development

Rationale: Study effect of electron cloud on dynamics of proton beam.

Present status:

The ORBIT E-Cloud Module is a stand-alone collection of C++ classes. It uses files of proton bunch particle coordinates generated by ORBIT.

Simulation model includes:

- **The 3D potential and density of the proton bunch.**
- **The 6D coordinates of the electrons in the E-cloud 3D and its potential and density.**
- **Initial electron generation induced by protons grazing the vacuum chamber.**
- **Initial electron generation induced by residual gas ionization.**
- **A secondary electron emission model. This model is essentially a simplified model of M. Pivi and M. Furman.**
- **The ability to include external magnetic and electrostatic fields.**

Ongoing and Future Development:

- **Improvement and benchmarking of the secondary electron emission model.**
- **Merging the original ORBIT code and the ORBIT E-Cloud Module.**
- **Apply electron cloud effects to proton beam.**

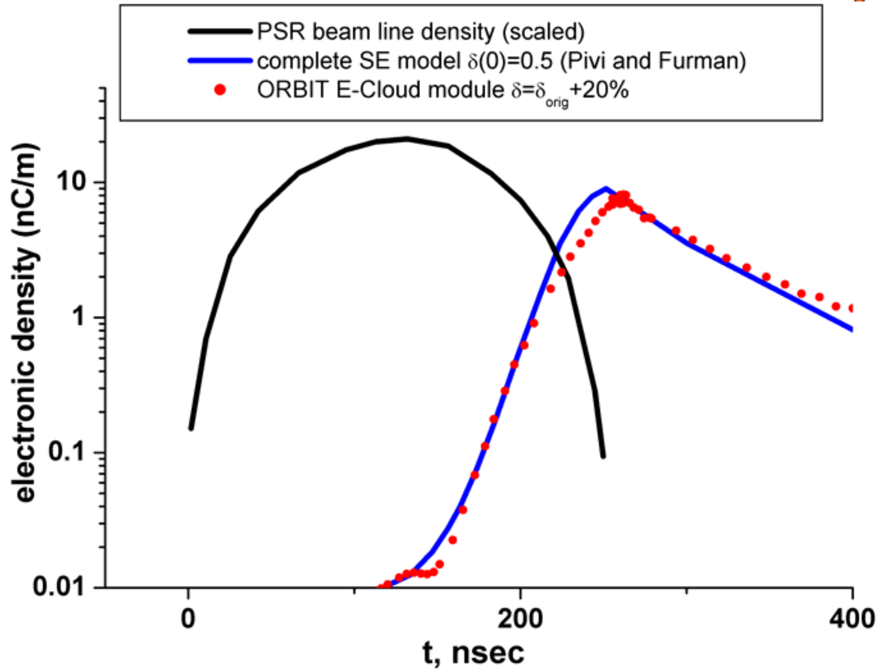
ORBIT E-Cloud Module Benchmark

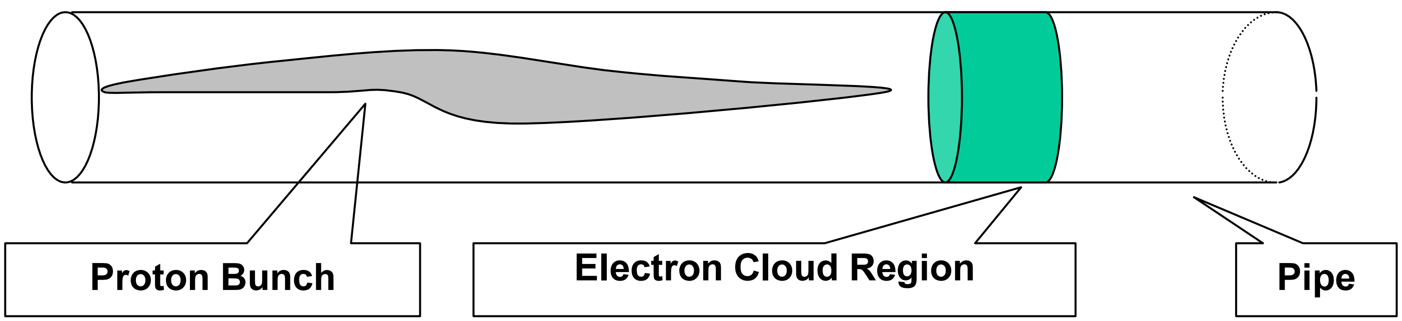
Simulated electron density during the first bunch passage (PSR)

ECE (Electron Cloud Effect) code
M.T.F. Pivi and M.A. Furman, LBNL
PRST AB V6 034201 (2003)

ORBIT E-Cloud Module

PSR beam line density





Conclusions

- The ORBIT Code, which was developed to perform realistic simulations of high intensity rings, and SNS in particular, is now being applied to a wide range of SNS ring issues.

- These applications require the continuing development of new models and code diagnostics
  - To increase the physics capabilities of ORBIT and
  - To align ORBIT more closely with actual accelerator applications.

- The results of these studies provide insight into the physics and the assurance to guide decisions.